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Basic Concepts and Applications of Prestressed Concrete

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1.1 Introduction

1.1.1 Basic Concepts of Prestressed Concrete

1.1.1.1 Basic Concepts

In the realm of civil engineering, concrete stands out as a favored material due to its impressive compressive strength. However, its tensile strength is notably limited (Naaman 2004). By incorporating reinforcements within areas of tension, the utility of concrete can be enhanced beyond that of its plain form (ACI 318-19 2019). Still, when concrete components are exposed to stresses like tension, eccentric compression, torsion, or bending, they remain susceptible to cracks, largely because of concrete's inherent tensile weakness.

For structures demanding exceptional resistance to cracking, such as vessels for nuclear power, oil storage facilities, or those located in highly corrosive settings, the use of reinforced concrete might not be optimal. Even in constructions where certain cracking is acceptable, it's crucial to keep the crack width within prescribed limits to ensure the structure's longevity and functionality. Current design standards typically allow for a crack width range of 0.3–0.4 mm. This translates to a maximum permissible tensile stress within the reinforcement at a crack between 250 and 400 MPa (Nawy 2006). Consequently, the use of high-strength materials in such contexts can be financially prohibitive.

Moreover, when it comes to crafting structures with extended spans, like beams, relying on reinforced concrete may not be the most practical choice. To manage the potential for cracks in such scenarios, there's a need to considerably expand both the sectional dimensions and the volume of reinforcements. Such alterations lead to a marked rise in the structure's self-weight relative to the overall design load, making the design financially less appealing (Nawy 2006).

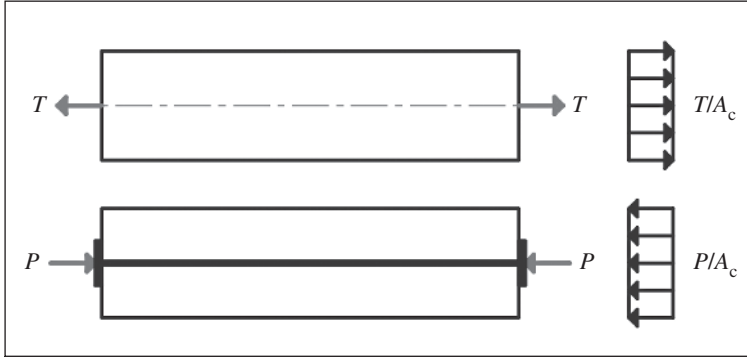


Figure 1.1 Illustration depicting the stress distribution within an axial tensile member.

Consider a situation wherein a concrete element is subjected to axial tension, as depicted in Fig. 1.1. As tension forces intensify, the tensile stress in the concrete surpasses its inherent tensile capability, leading to fractures. However, by employing high-grade steel rods encased in external polymer conduits within the concrete prior to setting, significant compressive stresses are induced within the concrete. These stresses manifest once the rods are anchored at both extremities, post their high-tension elongation, once the concrete achieves its required resilience. As illustrated in Fig. 1.1, under such conditions, the standard stress of concrete in a tensioned prestressed segment is computed as follows:

$$f^t = f^b = \frac{P}{A_c} - \frac{T}{A_c} \quad (1.1)$$

where f^t = stress at the top fibers.

f^b = stress at the bottom fibers.

P = the compressive force transferred to the concrete from the tensioned steel bars.

T = external applied tension force to the section.

A_c = concrete cross-sectional area.

Within the framework of a simply supported beam subjected to a uniform load distribution, the design employs tensioned parabolic steel cables affixed at the beam's terminal points, as illustrated in Fig. 1.2. The calculation of the typical stress in the concrete composition, especially at the lowermost surface fiber situated at the center span, is expressed as follows:

$$f^b = \frac{P}{A_c} + \frac{P \cdot e_b \cdot y_b}{I_g} - \frac{M \cdot y_b}{I_g} \quad (1.2)$$

where e_b represents the eccentricity. This relates to the alignment of the steel wires concerning the center of gravity of the concrete section, specifically at the midspan section.

y_b denotes the distance. It is taken from the center of gravity of the concrete section to its lowermost edge.

I_g symbolizes the moment of inertia, which is specific to the concrete section.

M is indicative of the bending moment. This is produced at the midspan due to the exertion of a uniformly spread load.

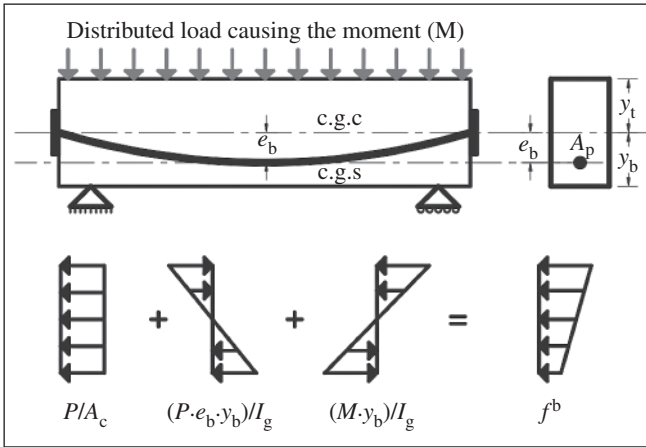


Figure 1.2 Illustration displaying the stress distribution observed at the midspan section of a simply supported beam.

When the compressive stress imposed on concrete by prestressed tendons exceeds the tensile stress arising from a uniformly distributed load, the tension zone experiences a complete absence of tensile stress. Prestressed tendons, also known as prestressing steels, are utilized to achieve this effect, generating a force called the prestressing force. The stress present in the concrete prior to loading, known as prestress, characterizes prestressed concrete structures, which intentionally incorporate prestress before service. In these structures, such as tension members (Fig. 1.1) and flexural members (Fig. 1.2), the compression transferred from the prestressing force modifies internal forces and alters stress distributions within sections. To eliminate or minimize tensile stress in concrete during service, the stress induced in the tendons during prestressing should be sufficiently high, accounting for all stress losses. Hence, high-tensile-strength materials are employed for the tendons to fully exploit their strength properties.

1.1.2 The Functions of Prestressing Force

The primary function of prestressing force in concrete structures is to counteract the tensile forces that develop when a structure is loaded. When a structure is subjected to external loads, such as the weight of a building or the forces caused by wind or earthquakes, the concrete is subjected to tensile stresses. Since concrete is relatively weak in tension, these stresses can cause cracking and even failure of the structure.

Prestressing force is applied to the concrete before it is loaded so that it can resist the tensile forces that will develop when it is in use. This is achieved by inducing compressive forces in the concrete using tendons that are anchored to the structure. When the tendons are tensioned, they generate compressive forces in the concrete, which creates a state of pre-compression. This pre-compression ensures that when the structure is loaded, the concrete is initially in a state of compression, which makes it more resistant to the development of tensile stresses.

Another function of prestressing force is to reduce deflection in the structure. Deflection is the deformation of a structure under load, and it can cause cracks and other forms of damage. By pre-compressing the concrete using prestressing forces, the deflection of the structure is reduced, making it more rigid and less prone to deformation (Fang et al. 2023; Nawy 2006; Pérez 2023; Seręga and Faustmann 2022).

Prestressing force can also improve the durability of concrete structures by reducing the effects of shrinkage and creep. Shrinkage is the reduction in volume of concrete as it dries, while creep is the gradual deformation of concrete under sustained load. Both of these phenomena can cause cracking and deformation in concrete structures, but by pre-compressing the concrete, the effects of shrinkage and creep are reduced (Asamoto et al. 2014; Nawy 2006; Wendling et al. 2018).

In addition to these functions, prestressing force can enhance the fire resistance of concrete structures. When concrete is subjected to high temperatures, it can lose its strength and fail. However, when concrete is pre-compressed using prestressing forces, it can maintain its strength and rigidity even at high temperatures. This makes it more resistant to fire damage (Nawy 2006).

In summary, the functions of prestressing force in concrete structures include counteracting tensile forces, reducing deflection, improving durability, and enhancing fire resistance. By pre-compressing the concrete using prestressing forces, the strength, durability, and performance of the structure are significantly enhanced, making it more resistant to damage from external loads, deformation, and other factors.

1.1.3 Prestress Level

The level of prestressing force that is applied to a concrete structure is a critical design consideration. The level of prestress must be carefully determined based on the intended use of the structure and the anticipated loads that it will experience during its lifetime. If the prestressing force is too low, the structure may not be able to resist the anticipated loads, while if the prestressing force is too high, it may cause the concrete to fail prematurely.

The level of prestressing force is determined by the design engineer based on a number of factors, including the strength of the concrete, the strength and size of the tendons, and the anticipated loads that the structure will experience. The level of prestress is typically expressed as a percentage of the concrete's compressive strength, with typical values ranging from 30% to 80% (Nawy 2006).

The level of prestress can affect the structural performance of the concrete in several ways. For example, a higher level of prestress can increase the strength and stiffness of the concrete, making it more resistant to deformation and deflection. However, a higher level of prestress can also increase the risk of cracking in the concrete, particularly if the structure is subjected to cyclic loading, such as from wind or earthquake forces (Nawy 2006).

The level of prestress can also affect the durability of the concrete structure. A higher level of prestress can reduce the effects of shrinkage and creep, as well as improve the fire resistance of the structure (Hou et al. 2013; Kumar and Kodur 2021). However, a higher level of prestress can also increase the risk of corrosion in the tendons, which can lead to structural damage over time (Nawy 2006).

In addition to the level of prestress, the distribution of prestress along the length of the tendons is an important design consideration. The prestress must be distributed evenly along the length of the tendons to ensure that the concrete is uniformly pre-compressed. If the prestress is not distributed evenly, it can cause local stresses and deformations in the concrete, which can lead to cracking and other forms of damage.

In summary, the level of prestressing force is a critical design consideration in concrete structures. The level of prestress must be carefully determined based on the intended use of the structure and the anticipated loads that it will experience. A higher level of prestress can improve the strength, stiffness, and durability of the structure, but it can also increase the risk of cracking and corrosion. The distribution of prestress along the length of the tendons is also important to ensure that the concrete is uniformly pre-compressed.

1.1.4 Prestressed Versus Reinforced Concrete

Prestressed concrete and reinforced concrete are both commonly used in construction, but they differ in the way they resist tensile stresses. Reinforced concrete relies on the inclusion of reinforcement bars or steel mesh to resist tensile stresses, while prestressed concrete uses pre-compression to resist these stresses (Nawy 2006).

In reinforced concrete, the reinforcement bars or steel mesh are embedded in the concrete and act as a sort of safety net to prevent the concrete from cracking under tensile stress. When the concrete is subjected to tensile stress, the reinforcement bars or steel mesh absorb the tensile force and distribute it throughout the structure, preventing the concrete from cracking or failing (Nawy 2006).

Prestressed concrete, on the other hand, relies on pre-compression to resist tensile stresses. Pre-compression is achieved by using tendons that are anchored to the structure and are then tensioned to generate compressive forces in the concrete. These compressive forces effectively “preload” the concrete with a state of compression, so that when the structure is subjected to tensile stress, the concrete is initially in a state of compression and can resist the tensile force.

One of the key advantages of prestressed concrete over reinforced concrete is that it can support larger loads with smaller cross-sections (Nawy 2006). By pre-compressing the concrete, the size of the cross-section required to support a given load can be reduced, making the structure more efficient and economical. This is particularly important in structures such as bridges and high-rise buildings, where minimizing the size and weight of the structure is critical.

Another advantage of prestressed concrete is that it is less prone to cracking and deformation than reinforced concrete (Nawy 2006). Because the concrete is pre-compressed, it is already under a state of compression when it is subjected to external loads, which reduces the development of tensile stresses and minimizes the risk of cracking and deformation.

However, there are also some disadvantages of prestressed concrete. It is more difficult and expensive to manufacture and install than reinforced concrete since it requires specialized equipment and skilled labor. It is also more susceptible to corrosion since the tendons used to pre-compress the concrete are typically made of steel and can corrode over time, leading to structural damage. Table 1.1 shows a summary of the key differences between reinforced and prestressed concrete construction.

Table 1.1 Comparison of key characteristics between reinforced and prestressed concrete construction methods.

Aspect	Reinforced concrete	Prestressed concrete
Tensile stress resistance	Relies on embedded reinforcement bars or steel mesh to resist tensile stress.	Utilizes pre-compression achieved through tendons to resist tensile stress.
Cross-section size	Requires larger cross-sections to support given loads.	Supports larger loads with smaller cross-sections, making structures more efficient.
Resistance to cracking and deformation	More prone to cracking and deformation under external loads.	Less prone to cracking and deformation due to pre-compression, providing greater durability.
Manufacturing and installation cost	Generally more cost-effective in terms of manufacturing and installation.	More difficult and expensive due to specialized-equipment and skilled-labor requirements.
Corrosion susceptibility	Less susceptible to corrosion since it relies on embedded steel bars or mesh.	More susceptible to corrosion as tendons are typically made of steel and can corrode over time.

In summary, prestressed concrete and reinforced concrete differ in the way they resist tensile stresses. While reinforced concrete relies on reinforcement bars or steel mesh to absorb tensile forces, prestressed concrete uses pre-compression to resist these forces. Prestressed concrete offers several advantages over reinforced concrete, including the ability to support larger loads with smaller cross-sections and greater resistance to cracking and deformation. However, it is also more difficult and expensive to manufacture and install, and more susceptible to corrosion.

1.1.5 Classification of Prestressed Concrete

Prestressed concrete can be classified in several ways based on different criteria, including the method of prestressing, the shape of the structure, and the type of load it supports.

1.1.5.1 Classification by Method of Prestressing

Prestressed concrete can be classified into two main types based on the method of prestressing: pre-tensioned and post-tensioned. Pre-tensioned concrete is manufactured by pre-tensioning the tendons before the concrete is cast (Nawy 2006). The tendons are anchored to the formwork and tensioned, and then the concrete is poured into the formwork. The concrete is allowed to set and cure, and then the tendons are released, transferring their pre-compression to the concrete. Pre-tensioned concrete is commonly used in precast concrete products such as beams, slabs, and hollow-core units.

Post-tensioned concrete, on the other hand, is manufactured by casting the concrete first and then post-tensioning it (Al Rawi et al. 2020; Jahami et al. 2020; Kobrosli et al. 2022). This is typically done by inserting ducts into the concrete and then tensioning the tendons after the concrete has set and cured. The tendons are then anchored, and the ducts are filled

with grout to protect the tendons from corrosion. Post-tensioned concrete is commonly used in bridges, high-rise buildings, and other large structures.

1.1.5.2 Classification by Shape of Structure

Prestressed concrete can also be classified based on the shape of the structure. Some common types of prestressed concrete structures include beams, slabs, columns, walls, and shells. Prestressed concrete beams are commonly used in bridges and buildings to support loads over long spans. They can be pre-tensioned or post-tensioned and are typically designed to resist bending and shear forces. Prestressed concrete slabs are used in floor and roof systems to provide a durable and stable platform for buildings. They can be pre-tensioned or post-tensioned and are typically designed to resist bending, shear, and deflection. Prestressed concrete columns are used to support vertical loads in buildings and bridges. They can be pre-tensioned or post-tensioned and are typically designed to resist bending and axial loads. Prestressed concrete walls can be used as load-bearing or non-load-bearing walls in buildings. They can be pre-tensioned or post-tensioned and are typically designed to resist bending, shear, and axial loads. Prestressed concrete shells are used in roof systems and other structures to provide a lightweight and efficient solution. They can be pre-tensioned or post-tensioned and are typically designed to resist bending and shear forces.

1.1.5.3 Classification by Type of Load

Prestressed concrete can also be classified based on the type of load it supports. Some common types of prestressed concrete structures based on load type include statically determinate structures, statically indeterminate structures, and cable-stayed structures. Statically determinate structures are those in which the loads can be calculated based on the geometry of the structure and the boundary conditions. They are typically simple structures such as beams and slabs. Statically indeterminate structures are those in which the loads cannot be calculated based on geometry alone, and additional information such as material properties and external loads is required. They are typically more complex structures such as bridges and high-rise buildings. Cable-stayed structures are those in which the load is transferred to the foundation through a series of cables that are anchored to the structure at various points. They are typically used in bridge construction and can be pre-tensioned or post-tensioned.

1.1.6 Materials and Techniques in Prestressed Concrete

1.1.6.1 Types of Concrete Suitable for Prestressing

Prestressed concrete's effectiveness is deeply interwoven with its inherent characteristics, which are carefully tailored to yield enhanced tensile strength and diminish the occurrence of cracks. A crucial factor determining the efficacy of prestressed structures is the choice of concrete type. High-strength concrete stands out prominently in prestressing applications. Its commendable compressive strength, often exceeding 6000 psi (41 MPa), ensures that the concrete section staunchly holds its ground against the considerable compressive forces exerted by the prestressing tendons (Fang et al. 2023; Liu et al. 2023).

However, in situations where the structure's dead weight is a consideration, the scales may tilt in favor of lightweight concrete. Crafted using lightweight aggregates such as expanded perlite or shale, this concrete variant strikes a harmonious balance between strength and weight. Its aptitude shines through in structures spanning longer distances or those aiming to curtail their self-weight (Li et al. 2021; Wu et al. 2021).

Navigating to scenarios where placing and consolidating concrete around prestressing tendons or ducts become intricate, self-consolidating concrete (SCC) emerges as a viable solution. Renowned for its exceptional flowability, SCC simplifies placement sans the reliance on mechanical vibration. This ensures that the tendons are completely ensconced and results in a more homogenized concrete section (Al-Negheimish et al. 2018a, 2018b).

Further enhancing the roster of concrete types is fiber-reinforced concrete (FRC). Infused with fibers—ranging from steel and polypropylene to carbon—FRC amplifies the post-crack tensile strength of the concrete (Camille et al. 2022; Peng et al. 2023). In the realm of prestressing, this trait is invaluable, as it meticulously curtails crack width and dissemination.

Lastly, when handling colossal prestressed structures, it becomes imperative to keep the heat generated during the hydration process in check. Low heat of hydration concrete enters the fray here. This concrete mix, characterized by its reduced heat production, becomes instrumental in staving off thermal cracking, thereby preserving the integrity of the prestressed member. Depicts various concrete types employed in prestressing applications.

To sum it up, the arena of prestressed concrete isn't solely confined to standard concrete mixes. The nuanced demands of prestressing compel the adoption of specific concrete types, each bringing a set of advantages to the table. These specialized concretes collectively amplify the performance, resilience, and lifespan of prestressed concrete structures, underscoring the importance of judicious selection tailored to the project's unique demands.

1.1.6.2 Prestressing Tendons: Materials and Properties

Prestressing tendons act as the critical structural components in prestressed concrete structures, bearing the responsibility of imposing compressive stress onto the concrete. This action balances the tensile stresses the concrete would likely undergo due to external loads. The efficiency of the prestressing process significantly hinges on the judicious selection of tendon material and a comprehensive understanding of its inherent properties.

When discussing materials, high-tensile steel emerges as the frontrunner, owing to its ubiquity in prestressing applications. The allure of high-tensile steel wires or strands lies in their remarkable strength coupled with their capability to endure tension without succumbing to permanent deformation. However, when battling the threats of corrosion, especially in environments where these risks are amplified, galvanized steel takes center stage. The protective zinc coating shields the tendons, prolonging the life and durability of the prestressed structures. In scenarios demanding even higher resistance to corrosion, like in the presence of chlorides or other aggressive agents, stainless steel tendons make their presence felt. While they carry a heftier price tag, their resilience often justifies the investment. Another material making strides in the realm of prestressing is carbon fiber-reinforced polymers (CFRP) (Hwang et al. 2023; Wang et al. 2023). As non-metallic tendons, their allure rests in their commendable tensile strength, featherlight

nature, and immunity to corrosion. Their adaptability shines, especially in projects centered around retrofitting and rehabilitation.

Diving into the realm of properties, the tensile strength of tendons becomes paramount. It dictates the quantum of force the tendon can exert on the concrete. The prowess of a tendon's tensile strength directly impacts the magnitude of prestressing force, which in turn influences the concrete's ability to resist tensile stresses. Bond strength, another vital property, speaks of the tendon's capability to form a cohesive unit with the surrounding concrete. This bond strength serves as a bridge for stress transfer from the tendon to its concrete encasement. Two intertwined properties—elasticity and elongation—define a tendon's resilience and adaptability. While elasticity ensures that a stretched tendon reverts to its original state, ensuring consistent compressive force application, elongation quantifies the stretch potential during prestressing. Structures like bridges, which confront varying loads, shine a spotlight on another crucial property: fatigue resistance. This property evaluates a tendon's tenacity against cyclic loading, ensuring that it can brave repeated loads without faltering (Deng et al. 2022; Du et al. 2020). Finally, corrosion resistance underscores the longevity perspective, guaranteeing that the embedded tendons maintain their integrity over prolonged periods, ensuring the structure's durability.

To encapsulate, the essence of prestressed concrete structures' performance, durability, and lifespan is significantly tied to the tendons' materials and properties. Tailoring tendon selection to align with a project's unique demands can unlock the full potential of prestressing, ensuring enduring structural benefits.

1.1.6.3 Adhesion and Bonding Mechanisms

The interplay between the prestressing tendons and the encasing concrete forms a pivotal aspect of the efficacy of prestressed concrete members. It's the strength of this bond that facilitates the seamless transfer of stresses and underpins the structure's integrity. Delving deeper into this, several facets of adhesion and bonding mechanisms emerge in the context of prestressed concrete.

Mechanical bonding takes the forefront, with roughened surfaces on the tendon being a primary strategy to amplify bond strength. This roughness promotes mechanical interlocking with the concrete. Beyond just surface treatment, tendons can be crafted with specific features like indentations, ribbings, or diverse patterns. These design choices not only increase the surface area for bonding but also set the stage for mechanical interlocking points, thereby augmenting bond strength.

Chemical bonding introduces another dimension. Contemporary prestressed systems occasionally resort to adhesive agents or bonding grouts. These agents bridge the chemical divide between the tendon and the immediate concrete, ensuring a stronger bond. This method becomes particularly pertinent in post-tensioned systems where the tendons might be sheathed in protective ducts.

On the other hand, frictional bonding capitalizes on the stresses inherent in the system. When the tendon exerts a compressive force onto the concrete, the resulting friction at the interface between the two materials acts as a resistance, further contributing to bond strength. This mechanism finds particular relevance in post-tensioned systems where the tendon is tensioned after the concrete sets.

Table 1.2 Bonding mechanisms in prestressed concrete.

Bonding mechanism	Description
Mechanical bonding	Achieved through roughened tendon surfaces, promoting mechanical interlocking with the concrete. Specific features like indentations, ribbings, or patterns enhance surface area and mechanical interlocking.
Chemical bonding	Utilizes adhesive agents or bonding grouts to bridge the chemical gap between the tendon and the concrete, fostering a stronger bond. Particularly relevant in post-tensioned systems with sheathed tendons.
Frictional bonding	Capitalizes on friction at the interface between the tendon and concrete when the tendon exerts compressive force, acting as resistance that enhances bond strength. Commonly applied in post-tensioned systems after concrete sets.
Grouting techniques	In post-tensioned systems, ducts are filled with grout post-stressing. This process shields against corrosion, enhances adhesion, and ensures continuous tendon-concrete contact.

Grouting techniques also play a substantial role, especially in many post-tensioned systems. Once the tendons have been stressed, the surrounding ducts are inundated with grout. This process is multipurpose: it acts as a shield against corrosion for the tendons, augments the bond via adhesion, and ensures that the tendon remains in intimate contact with the concrete throughout its length (Kumar et al. 2008; Saeed et al. 2020; Xiong et al. 2023).

However, understanding the bond is incomplete without recognizing the factors that might erode it. Corrosion stands as a significant threat, especially with steel tendons that, when exposed to moisture or aggressive chemicals, can deteriorate. This corrosion undermines not just the tendon’s strength but the bond it shares with the concrete. Similarly, influences that lead to microcracking in the concrete, be it external loadings or environmental factors like freeze–thaw cycles, have the potential to disrupt this bond. Other inherent properties of concrete, such as shrinkage or the phenomenon of creep, can also influence bond strength, more so in structures that face substantial restraint.

For prestressed concrete structures to deliver on their promise of performance and safety over extended periods, the bond between the tendon and the concrete must be robust and resilient. The onus is on engineers and researchers to innovate continually, refining techniques and harnessing new materials to fortify this bond. Such advancements ensure that the myriad advantages of prestressing find their full expression across a spectrum of applications. Table 1.2 summarizes the basic bonding mechanisms in prestressed concrete.

1.1.7 Advantages and Limitations of Prestressed Concrete

1.1.7.1 Superior Load-Bearing Capacity of Prestressed Concrete

Prestressed concrete is notable for more than just its distinct method of construction. A standout aspect is its enhanced mechanical performance, especially concerning its load-bearing capability. This elevated load-bearing capacity sets prestressed concrete apart from traditional reinforced concrete and a variety of other construction materials.

Central to the concept of prestressing is an ambition to address the tensile stresses that appear in a concrete member during its loading. Through the introduction of compressive

stresses in advance, the extent to which the concrete can withstand applied loads without yielding to tensile cracking is dramatically increased. Several mechanisms underscore this heightened load-bearing capacity.

When a prestress is administered to the concrete, the resulting tensile stresses, which are a consequence of external loads, are neutralized before they have a chance to initiate cracking. As a result, compared to a non-prestressed version, a prestressed concrete beam can endure a more substantial load before manifesting any distress signs. Furthermore, a marked difference between conventional reinforced concrete and prestressed concrete lies in the usage of the concrete's depth. In the standard variant, the concrete portion under tension (like the area below the neutral axis in a basic supported beam) offers limited resistance to bending, given the concrete's inherent weakness in tension. Conversely, due to the compressive stresses it undergoes, a more significant cross-section of the prestressed concrete effectively counters loads.

An added advantage is the tangible reduction in cracking. Even when subjected to considerable loading, the structures made from prestressed concrete show only minimal cracking. This diminished cracking not only heightens aesthetic appeal and longevity but also maintains the section's load-bearing prowess almost intact. Moreover, the usual recourse to high-strength concrete and high-tensile steel for prestressed operations inherently augments the member's load-bearing capacity.

Certain construction applications distinctly benefit from this superior load-bearing ability. These include long-span bridges, where the combination of vast spans without the need for intermediate supports makes prestressed concrete an excellent choice. High-rise buildings and skyscrapers also rely on this enhanced load-bearing feature to ensure both stability and safety. The same applies to industrial facilities that accommodate weighty machinery or undergo substantial dynamic loading. Similarly, structures like water tanks and silos, designed to contain considerable volumes of materials or liquids, necessitate an architecture with exceptional load-bearing capacities.

Drawing a comparison with other materials, metals like steel indeed boast impressive load-bearing capacities. However, they fall short in providing the fusion of compressive strength, durability, and fire resistance characteristic of concrete. By marrying the intrinsic advantages of concrete with the augmented tensile efficiency due to prestressing, we are left with a material that presents a holistic performance that's unparalleled.

In wrapping up, the exceptional load-bearing capacity of prestressed concrete signifies more than just an ability to support immense weights. It embodies delivering unwavering, trustworthy performance across diverse applications, diminishing the need for regular maintenance, and promising extended lifespan. Whether it's bridging expansive gaps, reaching great heights, or merely offering a steadfast foundation, in the realm of modern construction, prestressed concrete emerges as a preferred material.

1.1.7.2 Control Over Deflections in Prestressed Concrete

Deflections, the deformations seen in structural components when loads are applied, significantly impact a structure's serviceability and overall performance. Prestressed concrete stands out in this area, giving superior control over these deflections compared to its counterpart, traditional reinforced concrete. Let's delve deeper into the reasons behind this advantage.

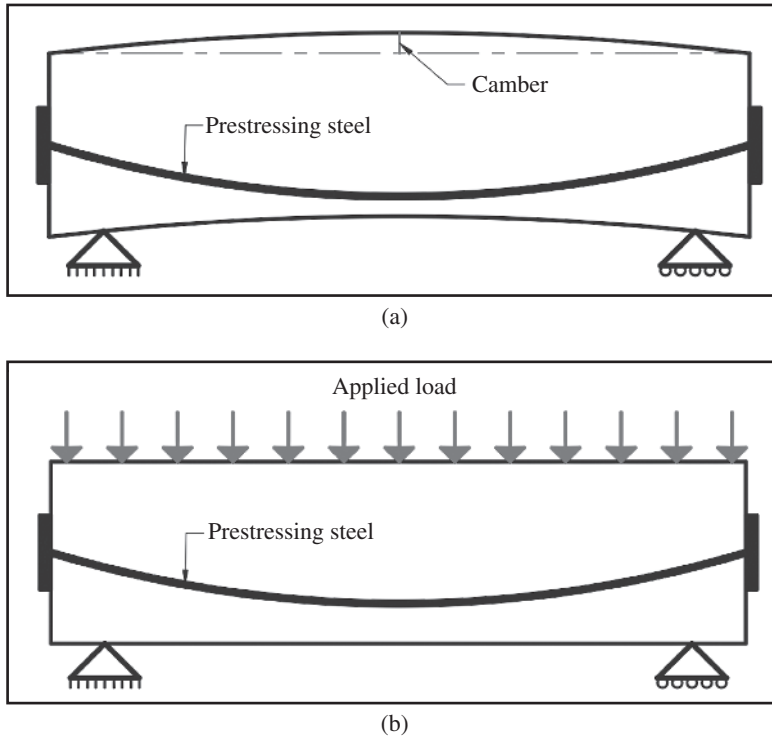


Figure 1.3 Upward camber example due to the prestressing effect at the transfer stage. (a) Camber in a Prestressed Concrete Beam and (b) Prestressed Concrete Beam Under Uniform Load.

At the heart of prestressing is the concept of pre-compressing the concrete member. Before any external loads come into play, these compressive stresses are introduced. The advantage here is that this pre-compression counterbalances a substantial amount of tensile stresses that typically result from bending when loads are applied. This balance, in effect, diminishes the deflection resulting from these loads.

Further, there's an enhancement in the section modulus of prestressed concrete members. This improvement comes from their capability to effectively use a more significant portion of the concrete's depth, as previously discussed in the context of load-bearing capacity. The direct implication of a heightened section modulus is the reduction in deflections when loads are put on the structure.

Moreover, the act of applying the prestressing force can induce an upward camber in the member, a type of deflection (Fig. 1.3). This upward curve serves as a countermeasure to the downward deflections that occur due to applied loads, leading to an overall decrease in net deflections.

The benefits of this reduced deflection are manifold. Firstly, it offers an aesthetic advantage. Deflections that are visible and appear excessive can mar the appearance of a structure and might indicate structural vulnerability, even when the structure is sound. By curbing these deflections, prestressed concrete amplifies the aesthetic allure of the built environment.

Furthermore, in structural components like roofs or floors, minimized deflection stops the potential pooling or ponding of water. This prevention is essential as pooled water can instigate issues like water infiltration or other structural complications.

There's also the matter of structures that house sensitive equipment, like in certain industrial settings or laboratories. In these spaces, even the slightest deflections can disrupt operations. The rigidity that prestressed concrete introduces becomes invaluable here. Moreover, reduced deflections translate to the decreased possibility of cracking, implying enhanced durability and lesser demands for maintenance.

Certain applications demand rigorous control over deflections. Among these are long-span beams and slabs. With increased spans comes an augmented potential for deflection, making prestressed concrete a prime choice to ensure that these deflections remain minimal. Similarly, cantilevered structures, due to their specific support conditions, are naturally predisposed to deflections. Here again, prestressed concrete brings the necessary rigidity. Pedestrian bridges, where the users can directly perceive deflection, demand minimal movement to ensure users' comfort and trust in the structure.

However, while the deflection control in prestressed concrete is remarkable, designers must not overlook the design code guidelines. Elements like the magnitude and duration of loads applied, the prestress level, and the long-term impacts of concrete's creep and shrinkage all play roles in influencing deflections.

In sum, prestressed concrete's ability to manage deflections combines aesthetic grace with structural soundness. Structures, when well-designed and constructed, not only function efficiently but also exude robustness. Thus, prestressed concrete, when utilized aptly, can elevate the quality and longevity of our built environments.

1.1.7.3 Potential Challenges in the Construction of Prestressed Concrete

Prestressed concrete, despite its advantages in performance and longevity, poses specific challenges during its construction. Understanding and anticipating these challenges are essential for their proper management during the design and construction phases.

A primary challenge in the construction of prestressed concrete is the need for specialized knowledge and expertise. This specialization is essential both in the design and execution stages. Errors can occur when engineers or workers are not adequately familiar with the intricate details of prestressed concrete. To address this, it's crucial that the construction team has appropriate training and hands-on experience with this type of concrete. Regular workshops, courses, and training sessions can help fill any knowledge gaps.

Furthermore, there's the issue of the high initial costs associated with prestressed concrete. Due to the requirement of high-strength materials, specific tensioning equipment, and the precision necessary, the upfront costs can be significantly higher than those of traditional construction methods. However, it's essential to note that, over the lifespan of the structure, these initial costs can often be recouped through reduced maintenance expenses and increased durability. Therefore, a holistic view that considers long-term benefits against immediate costs is advisable.

The act of tensioning the tendons demands precise equipment and close monitoring to ensure that the applied prestress remains within acceptable boundaries. This precision can be maintained through the regular calibration of equipment and the integration of modern monitoring technologies.

Another concern is the potentially slower construction speed due to the precision and the multiple steps inherent in prestressing, such as tensioning, anchoring, and possibly grouting. However, this can be mitigated by efficient project management and, where suitable, the incorporation of precast prestressed components, which can expedite the overall construction timeline.

There are also durability concerns, especially in environments characterized by high salinity or the presence of corrosive agents. In such conditions, tendons, particularly if exposed or located within voided ducts, risk corrosion. Addressing this requires measures like thorough duct grouting, the use of corrosion-resistant tendons such as those coated with epoxy or galvanized, and the application of protective sealants.

Over-stressing is another potential risk. Without adequate monitoring, the concrete could be subjected to excessive stress during tensioning, leading to possible cracking or even devastating structural failure. This risk highlights the need for rigorous quality control, calibrated equipment, and real-time monitoring during the tensioning phase.

Lastly, the inherent complexities in prestressed concrete mean that any modifications or repairs can be more challenging than in standard reinforced concrete structures, especially if the tendons are internal. For this reason, comprehensive documentation of the original build, coupled with the employment of nondestructive testing techniques, is crucial when undertaking any modifications or repairs.

In summation, while prestressed concrete promises many advantages, its construction demands careful consideration and attention. By recognizing the potential challenges and addressing them head-on, both engineers and builders can realize the full potential of prestressed concrete, ensuring that the built structures are safe, efficient, and enduring.

1.1.8 Safety and Durability Aspects

1.1.8.1 Resistance to Environmental Factors in Prestressed Concrete

The endurance and lifespan of structural materials hinge largely upon their resilience against the damaging influences of environmental factors. This resilience is particularly accentuated in the case of prestressed concrete, making it a material of choice in challenging environments.

One of the formidable challenges in colder climates is the freeze–thaw cycle, where the cyclic freezing and melting of trapped water within the porous structure of concrete can precipitate microcracking, spalling, and subsequent decay (Qin et al. 2016b). Yet, the compressive stresses in prestressed concrete diminish the size and frequency of these capillaries and pores. This densification curbs water absorption and renders the concrete more resistant to the ravages of freeze–thaw cycles.

Equally challenging is the issue of chloride ion penetration, especially in marine environments or areas employing de-icing salts. This penetration can expedite the corrosion of the reinforcing steel, undermining structural integrity. However, prestressed concrete, courtesy of its superior quality and density around the tendons, coupled with protective interventions like the grouting of ducts, considerably mitigates the threat of chloride intrusion and ensuing corrosion.

Another menace is the alkali–silica reaction (ASR), a chemical interplay between the alkalis in cement and reactive silica present in aggregates. The resultant gel, upon

imbibing moisture, swells, leading to pressures that can cause cracking. The counteracting compressive stresses in prestressed concrete can somewhat dampen the expansive repercussions of ASR. The judicious selection of nonreactive aggregates and the incorporation of supplementary cementitious materials further diminish ASR risks.

Carbonation, the process in which atmospheric carbon dioxide reacts with calcium hydroxide in concrete, forming calcium carbonate, poses yet another challenge. This alters the concrete's alkalinity, potentially endangering the passive protection offered to the reinforcing steel. Yet, the compactness of prestressed concrete hinders the swift penetration of carbon dioxide, decelerating the carbonation process. Furthermore, the encasement of tendons, especially evident in post-tensioned systems, provides an additional protective layer.

In certain industrial settings, the presence of acids can assail concrete, eroding its mass and compromising its strength. The inherent low permeability and reduced porosity of prestressed concrete obstruct the entry of these corrosive agents. In exceptionally aggressive settings, the integration of acid-resistant aggregates or specialized cement formulations augments this resistance further.

Lastly, the encounter with sulfates, present in some soils or water sources, can be deleterious. These sulfates can react with the hydrated calcium aluminate in the cement matrix, initiating expansive reactions and consequent degradation. However, the deployment of sulfate-resisting cement, combined with the attributes of dense and impermeable concrete, notably reduces the vulnerability of prestressed structures to sulfate aggression.

To sum up, the intrinsic characteristics of prestressed concrete, especially its density, decreased porosity, and superior quality, render it remarkably adept at warding off diverse environmental challenges. This formidable environmental fortitude is a compelling reason for the widespread adoption of prestressed concrete in structures situated in adverse conditions, assuring an extended lifespan with minimized maintenance requirements.

1.1.8.2 Fire Resistance in Prestressed Structures

Understanding the fire resistance of structures necessitates a comprehensive grasp of how materials and components interact with intense heat and their ability to retain structural integrity during and post a fire incident. While prestressed concrete parallels its traditional counterpart in offering intrinsic fire resistance, it demands special attention due to its distinct design and materials.

Concrete, by its nature, is generally noncombustible and exhibits a slow heat transfer rate. This quality ensures that the escalating temperatures during a fire are absorbed gradually, postponing the manifestation of internal structural damage. In the context of prestressed structures, the denseness of the material further fortifies its resilience, courtesy of its reduced porosity that decelerates heat penetration.

However, when considering the steel tendons pivotal in prestressing, vulnerabilities emerge. These tendons, although encased in concrete or safeguarded by protective ducts, may be susceptible to prolonged exposure to high temperatures. This exposure can culminate in a diminishing yield strength of the steel and a potential relaxation of the prestress. These vulnerabilities underscore the significance of ensuring a generous concrete cover over the tendons and advocating the use of fire-resistant grouts. Notably, in post-tensioned systems, the incorporation of fully grouted ducts presents an extra protective barrier.

Another concern is the phenomenon of thermal expansion in concrete when confronted with acute heat. Moreover, the rapid heating of trapped moisture might trigger explosive spalling, leading to the concrete's surface layer disintegrating. Interestingly, the compressive stress inherent in prestressed concrete can sometimes mitigate the likelihood of such explosive spalling. But, to further curtail this risk, it becomes imperative to employ concrete mixes characterized by low water content and permeability.

A challenge that remains consistent across all concrete structures, including the prestressed variants, is the potential deformation when subjected to fire. This deformation arises primarily due to thermal expansion coupled with the weakening of material strength under escalated temperatures. Counteracting this challenge calls for the integration of supplementary cementitious materials, like fly ash or slag, which bolster the concrete's defense against deformation during fire exposure. Reinforcing proper anchorage and meticulous detailing can further enhance stability during fiery ordeals.

Subsequent to a fire incident, the assessment of potential damages to the prestressed structure, especially concerning tendons, becomes paramount. Techniques such as nondestructive tests, including sonic echo or impact-echo examinations, emerge as pivotal tools to gauge the tendons' post-fire integrity. Concurrently, the analysis of concrete core samples can offer insights into the depth of internal damages.

Lastly, it's worth noting that existing design codes provide exhaustive guidance on the fire-resistant design of concrete structures, prestressed included (ACI Committee 318, American Concrete Institute 2019; British Standards Institution 2000; National Fire Protection Association 2020). Adhering scrupulously to these guidelines ensures that structures can navigate standard fire scenarios without succumbing to catastrophic failures. Ensuring adequate concrete cover, integrating fire-resistant additives in the mix, and incorporating potential fire effects during the design phase can substantially bolster the fire resilience of prestressed entities.

Conclusively, the fire resistance of prestressed concrete structures, although inherently robust, demands nuanced considerations unique to prestressing. Through astute design, material selection, and rigorous post-event evaluations, these edifices can be optimized to confront fire hazards, ensuring their enduring safety and stability.

1.1.8.3 Structural Health Monitoring and Maintenance of Prestressed Concrete

The longevity and safety of infrastructures are core pillars in the realm of civil engineering, making the structural health monitoring (SHM) of structures throughout their life cycle an essential endeavor. Especially in the context of prestressed concrete, the monitoring and upkeep of system integrity ascend to paramount importance given its distinct characteristics and inherent vulnerabilities.

Delving into the importance of SHM in prestressed structures, it's evident that the prestressing force, owing to its crucial role in dictating structural behavior, demands close attention. Any deviation, be it from corrosion, tendon rupture, or anchor slippage, can dramatically impact the structure's health. The early detection of such alterations, afforded by SHM, is therefore vital.

Several advanced techniques have been developed for SHM in the domain of prestressed concrete. One such method is acoustic emission monitoring, which relies on detecting energy release, such as that from tiny crack formations, pointing toward anomalies like

tendon ruptures or anchor issues. Vibration-based monitoring offers insights into structural health by studying changes in the vibrational characteristics of a structure, thereby identifying potential issues like loss of prestress or overt structural damage. Another noteworthy technique is the use of fiber optic sensors. Whether embedded in the concrete or affixed externally, these sensors meticulously measure strain changes, shedding light on issues lurking within the prestressed system.

Maintenance of prestressed concrete structures also has its unique considerations. For instance, corrosion protection is vital due to the steel composition of the tendons in most prestressed systems. This emphasizes the need for meticulous inspection of grouting quality, assuring adequate concrete cover, and the adoption of corrosion-inhibiting admixtures. Furthermore, as the prestress in tendons can wane over time because of stress relaxation, periodic evaluations and potential re-tensioning become necessary. Equally significant is the quality of grout, especially in post-tensioned systems, where guarding against voids, cracks, or sub-par grout can fend off moisture penetration and the ensuing corrosion.

Integrating SHM with maintenance regimes has paved the way for a more nuanced approach to infrastructure care. Through consistent or periodic data gathering via SHM, maintenance endeavors become more pinpointed, nipping budding issues in the bud before they exacerbate. Furthermore, leveraging advanced algorithms allows for predictive maintenance, where SHM data can be analyzed to forecast potential component failures or impending maintenance requirements.

The overarching benefits of comprehensive SHM and rigorous maintenance are manifold. Not only do these practices extend the service life of structures, but they also culminate in long-term cost savings by forestalling expensive repairs or overhauls. Above all, continuous surveillance ensures the early detection of any structural threat, upholding the safety of both users and the surrounding milieu.

To encapsulate, SHM and upkeep of prestressed concrete edifices are instrumental in ensuring their extended durability, uncompromised safety, and peak performance. With technological strides and the sophisticated integration of SHM systems, the stewardship of these infrastructures is evolving, promising sustained operationality for generations to come. Table 1.3 shows a summary of different safety and durability aspects in prestressed concrete.

1.2 Historical Evolution of Prestressed Concrete

The history of prestressed concrete unfolds as a narrative of human innovation and the continual pursuit to transcend the innate limitations of construction materials. Tracing its roots to the late 19th century, the foundational concept of prestressed concrete emerged from the ambition to augment the inherent compressive strength of concrete and counteract its weak tensile strength. During these early years, several European patents related to prestressed concrete were documented. However, while the foundational theory of prestressing was acknowledged, its widespread application was curtailed until the 20th century, predominantly due to the absence of appropriate high-strength materials and effective bonding methodologies.

Table 1.3 Comprehensive overview of prestressed concrete aspects.

Aspect	Environmental resistance	Fire resistance	Structural health monitoring (SHM) and maintenance
Environmental factors	Freeze–thaw cycle, chloride ion penetration, alkali–silica reaction (ASR), carbonation, acid attack, sulfate attack	Impact of fire on prestressed structures, thermal expansion, spalling	Monitoring of prestressing force, acoustic emission, vibration-based monitoring, fiber optic sensors
Prestressed concrete mitigation	Densification reduces capillaries and pores, resistance to chloride intrusion, diminished ASR risk, reduced carbonation rate, low permeability and reduced porosity, corrosion resistance to acids, sulfate resistance	Noncombustible, low heat transfer rate, protection of steel tendons, low water content mixes, low risk of explosive spalling	Early detection of issues, strain measurements, fire-resistant grouts, predictive maintenance, corrosion protection, re-tensioning
Key considerations	Grouting quality, concrete cover, selection of nonreactive aggregates, incorporation of supplementary cementitious materials	Adequate concrete cover, fire-resistant grouts, low water content mixes, deformation control, anchorage quality	Advanced algorithms, predictive maintenance, moisture protection, inspection of grout quality, post-fire evaluation
Benefits	Extended lifespan, reduced maintenance, cost savings	Structural integrity, delayed spalling, controlled thermal expansion	Early issue detection, enhanced stability, cost savings, safety assurance

The onset of the 20th century witnessed transformative developments in the domain of prestressed concrete. The 1920s, in particular, stood out as a pivotal decade when French engineer Eugène Freyssinet, often regarded as the pioneer of modern prestressed concrete, achieved success in constructing an array of prestressed concrete structures. Freyssinet’s groundbreaking work relied on the use of high-strength steel wires, which were instrumental in introducing compressive stresses into the concrete. Following on Freyssinet’s heels, the subsequent decades, stretching from the 1930s to the 1950s, saw the blossoming of pre-tensioned and post-tensioned systems. This era marked the erection of iconic prestressed infrastructures, predominantly bridges, beams, and edifices, prominently in Europe and the United States. The devastation of World War II inadvertently set the stage for the extensive adoption of prestressed concrete during the extensive postwar reconstruction. The material’s inherent ability to achieve extended spans without the need for intermediate supports rendered it an optimal choice, especially in bridge construction.

Subsequently, the latter half of the 20th century was characterized by substantial advancements in materials and technology. The introduction of high-strength steel

tendons during this period revolutionized the application of prestressing forces, paving the way for the design and construction of more slender and elongated structures. Parallel to this, the inception of enhanced grouting materials fortified the protection of tendons and ameliorated bonding in post-tensioned systems. As the 20th century drew to a close and the world stepped into the new millennium, the applications of prestressed concrete diversified, encompassing not only bridges and beams but also expanding to include structures like slabs, silos, tanks, and even nuclear containment facilities. This modern era also witnessed the birth of innovative prestressing techniques, such as external prestressing, propelled by leaps in computational capabilities. In tandem with the global emphasis on sustainable construction, prestressed concrete began to be recognized for its eco-friendly attributes, including its durability, efficiency in material usage for expansive spans, and its recyclability potential.

Concluding this historical overview, it's imperative to acknowledge the role of evolving standards and codes in shaping the trajectory of prestressed concrete. As comprehension of the behavior of prestressed concrete deepened over the decades, a plethora of standards and design codes mushroomed across nations. These codes, grounded in empirical research and lessons from past failures, have been instrumental in ensuring the safe and effective design and construction of prestressed structures. In essence, the journey of prestressed concrete, from its embryonic stages in the 19th century to its omnipresent status today, stands as a monumental testament to the dynamic evolution of engineering and the relentless quest for constructional excellence.

References

- ACI 318-19 (2019). *Building Code Requirements for Reinforced Concrete*. Farmington Hills, MI: American Concrete Institute.
- ACI Committee 318, American Concrete Institute (2019). Building code requirements for structural concrete (ACI 318-19): an ACI standard : commentary on building code requirements for structural concrete (ACI 318R-19). American Concrete Institute, Farmington Hills, Mi.
- Al Rawi, Y., Temsah, Y., Baalbaki, O. et al. (2020). Experimental investigation on the effect of impact loading on behavior of post- tensioned concrete slabs. *Journal of Building Engineering* 31 (January): 101207. <https://doi.org/10.1016/j.jobbe.2020.101207>.
- Al-Negheimish, A.I., El-Sayed, A.K., Khanbari, M.O., and Alhozaimy, A.M. (2018a). Long-term deflection of prestressed SCC hollow core slabs. *Construction and Building Materials* 189: 181–191.
- Al-Negheimish, A.I., El-Sayed, A.K., Khanbari, M.O., and Alhozaimy, A.M. (2018b). Structural behavior of prestressed SCC hollow core slabs. *Construction and Building Materials* 182: 334–345.
- Asamoto, S., Kato, K., and Maki, T. (2014). Effect of creep induction at an early age on subsequent prestress loss and structural response of prestressed concrete beam. *Construction and Building Materials* 70: 158–164. <https://doi.org/10.1016/j.conbuildmat.2014.07.028>.
- British Standards Institution (2000). Eurocode 2: design of concrete structures: part 1–2 general rules – structural fire design: BS EN 1992-1-2:2004. BSI, London.

- Camille, C., Mirza, O., Kirkland, B., and Clarke, T. (2022). Structural behaviour of prestressed concrete sleepers reinforced with high-performance macro synthetic fibres. *Engineering Failure Analysis* 141: 106671.
- Deng, Z., Huang, S., Wang, Y., and Xue, H. (2022). Experimental research on fatigue behavior of prestressed ultra-high performance concrete beams with high-strength steel bars. *Structure* 43: 1778–1789.
- Du, Y., Wei, J., Yuan, J. et al. (2020). Experimental research on fatigue behavior of prestressed concrete beams under constant-amplitude and variable-amplitude fatigue loading. *Construction and Building Materials* 259: 119852.
- Fang, Z., Tian, X., and Peng, F. (2023). Flexural strength of prestressed Ultra-High-Performance concrete beams. *Engineering Structures* 279 (January): 115612. <https://doi.org/10.1016/j.engstruct.2023.115612>.
- Hou, X., Zheng, W., and Kodur, V.K.R. (2013). Response of unbonded prestressed concrete continuous slabs under fire exposure. *Engineering Structures* 56: 2139–2148. <https://doi.org/10.1016/j.engstruct.2013.08.035>.
- Hwang, S.-H., Kim, J., Kim, T.-K. et al. (2023). Evaluation of transfer length of CFRP tendon in pre-tensioned concrete beam using embedded FBG sensors. *Structure* 54: 1744–1755.
- Jahami, A., Tamsah, Y., Khatib, J. et al. (2020). Impact behavior of rehabilitated post-tensioned slabs previously damaged by impact loading. *Magazine of Civil Engineering* 93 (1): 134–146. <https://doi.org/10.18720/MCE.93.11>.
- Kobrosli, H., Baalbaki, O., Jahami, A. et al. (2022). Influence of various design parameters of the grouted duct on mono-strand bond behavior in post tensioned members. *Journal of Materials Research and Technology* 17: 1232–1245. <https://doi.org/10.1016/j.jmrt.2022.01.034>.
- Kumar, K., Karthikeyan, M.S., and Palaniswamy, N. (2008). Evaluation of performance of grout materials in protection of prestressing steel. *International Journal of Electrochemical Science* 3: 315–324.
- Kumar, P. and Kodur, V.K.R. (2021). Response of prestressed concrete beams under combined effects of fire and structural loading. *Engineering Structures* 246 (August): 113025. <https://doi.org/10.1016/j.engstruct.2021.113025>.
- Li, S., Chen, W., and Zhang, Y. (2021). Flexural behavior of precast, prestressed, lightweight aggregate concrete-conventional concrete composite beams. *Construction and Building Materials* 274: 121926.
- Liu, G.Q., Liu, G., and Jiang, W. (2023). Modeling and calculation of shear capacity of prestressed high strength concrete beams with web reinforcement based on BIM. *Ain Shams Engineering Journal* 15 (1): 102360.
- Naaman, A.E. (2004). *Prestressed Concrete Structure Analysis and Design*, 2e. New York: McGraw Hill.
- National Fire Protection Association (2020). NFPA 502: standard for road tunnels, bridges, and other limited access highways 2020. National Fire Protection Association, Quincy, Massachusetts.
- Nawy, E.G. (2006). *Prestressed Concrete: A Fundamental Approach*, 5e. Upper Saddle River: Prentice- Hall Inc.
- Páez, P.M. (2023). A simplified approach to determine the prestress loss and time-dependent deflection in cracked prestressed concrete members, prestressed with fiber reinforced

- polymers or steel tendons. *Engineering Structures* 279 (January): 115523. <https://doi.org/10.1016/j.engstruct.2022.115523>.
- Peng, F., Xue, W., and Yu, T. (2023). Cyclic behavior of polypropylene fiber reinforced concrete beams with prestressed CFRP tendons and nonprestressed steel bars. *Engineering Structures* 275: 115201.
- Qin, X., Si, M., Cao, D. et al. (2016b). Evaluation of freeze-thaw damage on concrete material and prestressed concrete specimens. *Construction and Building Materials* 125: 892–904.
- Saeed, Y., Al-Obaidi, S., Al-Hasany, E.G., and Rad, F.N. (2020). Evaluation of a new bond-type anchorage system with expansive grout for a single FRP rod. *Construction and Building Materials* 261: 120004.
- Seręga, S. and Faustmann, D.H. (2022). Flexural strengthening of reinforced concrete beams using external tendons. *Engineering Structures* 252 (January 2021): 113277. <https://doi.org/10.1016/j.engstruct.2021.113277>.
- Wang, W., Xu, J., Xu, J. et al. (2023). A novel integrated sleeve-wedge anchorage system for multi-tendon CFRP cable utilized in cable roof structures: concept and numerical investigation. *Journal of Building Engineering* 76: 107404.
- Wendling, A., Sadhasivam, K., and Floyd, R.W. (2018). Creep and shrinkage of lightweight self-consolidating concrete for prestressed members. *Construction and Building Materials* 167: 205–215. <https://doi.org/10.1016/j.conbuildmat.2018.02.017>.
- Wu, T., Sun, Y., Liu, X., and Cao, Y. (2021). Comparative study of the flexural behavior of steel fiber-reinforced lightweight aggregate concrete beams reinforced and prestressed with CFRP tendons. *Engineering Structures* 233: 111901.
- Xiong, X., He, L., Zhou, Z., and Xiao, Q. (2023). The bond-slip constitutive model of retard-bonded prestressing steel strand. *Construction and Building Materials* 365: 129995.

